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Evaluating quaternary glacial till sheet volume and duration of grounding events using sediment flux calculations in the Eastern basin paleotroughs, Ross Sea, Anarctica

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EVALUATING QUATERNARY GLACIAL TILL SHEET VOLUME AND DURATION OF GROUNDING EVENTS USING SEDIMENT FLUX CALCULATIONS IN THE EASTERN BASIN PALEOTROUGHS, ROSS SEA, ANTARCTICA

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I dedicate this thesis to my grandparents George and Elva Kubera who bestow my family with ceaseless love and support and will forever be the most revered individuals in my life, I am truly blessed and honored that I can call myself their grandson; to my loving parents Timothy and Paula Kirst, who I am infinitely grateful to for raising me in a family that fosters unending love and support, as well as for initiating my fascination with geology; and to the many geoscientists around the world who contrive logic from chaos and interpret brilliance from obscurity in order to transform the abstract into reality.

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Abstract

A sequence of three seismically-resolvable, back-stepping grounding zone wedges (GZWs) within the Glomar-Challenger Basin paleo-ice-stream trough is conventionally interpreted to have been deposited by the West Antarctic Ice Sheet (WAIS) since the end of the Last Glacial Maximum (LGM). For this to be true, there would have to have been voluminous GZW deposition via fast moving ice streams with high sediment flux during the short timeframe since the WAIS retreat began at 11 Ka ^{14}C BP and when the WAIS moved south of Roosevelt Island at 3.2 Ka BP. In contrast to this interpretation of how the near-surface stratigraphy relates to post-LGM retreat of the WAIS, foraminiferal radiocarbon dates from Bart and Cone (2012) suggest that the youngest back-stepped GZW corresponds to the culmination of erosion and deposition during the LGM. If so, the older GZWs currently assigned to the post LGM time frame would need to be reassigned to pre-LGM glacial cycles. To test which of these interpretations is correct, the duration of the Brown Unit, the second of the three backstepped GZWs, was investigated in detail. Five seismic surveys from eastern Ross Sea were used to map the extent and thickness of the Brown Unit. Two end-member durations were deduced using 3D sediment flux values that would have existed were the WAIS in retreat mode versus advance mode. Utilizing the retreat-mode flux, a 5.12 ± 1 ky grounding event duration was calculated for the Brown Unit GZW. However, a 512.88 ± 100 ky grounding event duration was determined using the advance-mode sediment flux. Given the durations previously calculated for the Gray Unit (the youngest post-LGM GZW) from Bart and Owolana (2012) and the grounding event duration recently calculated for the Red Unit (the oldest post-LGM GZW) by Bowles (2013) suggests that the near surface stratigraphy must represent the amalgamation of erosion and

deposition from many cycles of WAIS advance and retreat. In particular, the Brown Unit is tentatively assigned to time elapsed between MIS5 and MIS8.

Introduction

Gaining knowledge of Antarctic Ice Sheet (AIS) behavior within the recent geologic past will help predict when future grounding line translations might occur and with what associated rates and magnitudes of eustatic fluctuations. Twenty five percent of the AIS drains into the Ross Sea with contributions from both the Western Antarctic Ice Sheet (WAIS) and Eastern Antarctic Ice Sheet (EAIS) (Shipp et al., 1999). Because of this substantial volume of ice-sheet drainage, the near-surface stratigraphy of Ross Sea is of great interest for establishing constraints on the recent retreat history of the WAIS. The stability of the WAIS is of particular interest because fast moving ice-streams create the possibility of a significant negative mass balance. Moreover, the WAIS is a marine-based ice sheet, meaning that most of the ice sheet is grounded on land that is far below sea level. Because of the marine-based nature of the WAIS, most of its termination is in contact with the ocean. Thus, the stability of the ice sheet is threatened by warm-water intrusion, which can significantly melt ice and cause retreat (Pollard and DeConto, 2009). Total collapse of the WAIS has occurred in the Quaternary (Scherer et al., 1998) and involved return of ice-volume to the global ocean sufficient to raise sea level by 5 to 6 meters (e.g., Hughes, 1973; Anderson 1999; Conway et al., 1999; Denton, 1999; Shipp et al., 1999; Mosola and Anderson, 2006; Bramber et al., 2009). To evaluate the future stability of the WAIS, better details on the chronology of the recent retreat are needed. The most dynamic and thus critically important component within ice sheet behavior is fast moving ice streams (Hughes, 1973). Ice streams move large volumes of ice to the ocean at +500m/year. The lengths of ice streams are in excess of 500 km, i.e., these high ablation zones extend far into the West Antarctic interior. The limit of grounded ice is called the grounding line. At the grounding line, subglacially eroded and transported sediment is deposited in a geomorphologic feature called a grounding zone wedge (GZW). GZWs are also referred to as till deltas (Alley et al., 1989). Earth's climatic system is ultimately driven by fluctuations in solar radiation reaching the planet. Climate fluctuations in turn influence the extent of grounded ice. Ice streams and the associated GZWs they produce delineate the various extents formerly occupied by grounded ice. In other words, the former positions of the ice sheet are recorded by GZW locations on the continental shelf. GZWs are composed of glacial till deposited at the marine terminus of the grounding line via fast flowing ice streams (Alley et al., 1989).

Geological and geophysical data strongly suggests that at the Last Glacial Maximum (LGM), the AIS advanced to the outer continental shelf (e.g., Bentley et al., 1999; Conway et al., 1999; Shipp et al., 1999). Ice sheet retreat from the outer shelf is usually assumed to have consisted of several pauses followed by lift-off retreats (Conway et al., 1999; Domack et al., 1999; Mosola and Anderson, 2006). The present inner shelf grounding line position marks the location to which the WAIS retreated since the last decoupling retreat (Figure 1). Anandrakrishnan et al. (2007) proposed that the WAIS has occupied this grounding line position for a millennium. GZWs between the shelf edge and the modern grounding line thus show the depositional boundaries of grounded ice during multiple pauses within an overall retreat (Bart, 2004; Mosala and Anderson, 2006; Bart and Owolana, 2012). Seismic data from the outer and middle shelf within the Glomar Challenger, Whales Deep, and Little America basins show several GZWs were deposited within the paleotroughs of WAIS ice streams (Bart, 2004; Mosala and Anderson, 2006; Anderson, 2007; Bart and Owolana, 2012).

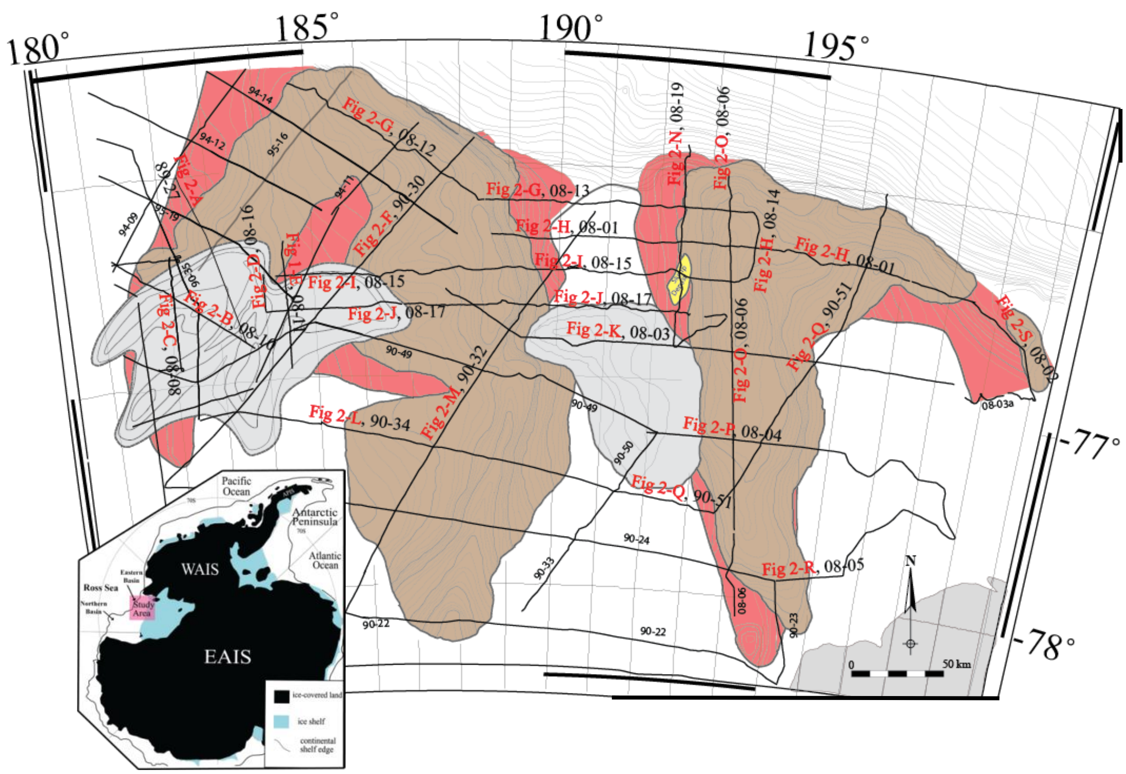


Figure 1: Bathymetric map of Eastern Ross Sea.

The Purple GZW was deposited first followed by sequential deposition of the Red and Brown Unit GZWs, which were followed by the middle shelf unit, the Gray Unit GZW (Bart, 2004).

A precise chronology for the stratigraphic succession would permit a better assessment of what factors control advance and retreat dynamics of the ice sheets. Previous studies have aimed to more precisely deduce the timing and evolution of individual liftoff retreats. Unfortunately, these studies have not yet provided detailed conclusions on which the community agrees. The lack of progress is due to the paucity of datable material within the glacial sediments (Licht et al., 1996; Conway et al., 1999; Bart, 2004; Mosola and Anderson, 2006; Bart and Cone, 2012; Bart and Owolana, 2012).

Due to the nature of the glacial depositional process, reworked sediment is abundant in the grounding line deposits on the shelf. This reworked material is difficult to eliminate from samples. The presence of reworked material with *in situ* carbonate material in the glacial sediment thus generates large uncertainties in the radiocarbon dates (Licht and Andrews, 2002). For this reason, conflicting interpretations of radiocarbon dates have been proposed that attempt to address the chronology of WAIS retreat. No study as of yet has established a chronology for successive GZW deposition. Most investigators use the existing data to conclude that open-marine sedimentation was occurring by 11 ka ^{14}C BP, i.e., the start of WAIS retreat from the outer shelf. This interpretation requires that older dates, suggesting earlier retreat of grounded ice, are excluded from consideration. From a synthesis of onshore and offshore data, Conway et al. (1999) proposed that ice retreated south of Roosevelt Island in the eastern Ross Sea by 3.2 ka ^{14}C BP. This date of retreat is based on modeling of in radar reflection data from Roosevelt Island, an ice rise formed when the Ross Ice Shelf became pinned to an underlying seafloor bank. Grounded ice continued to retreat to the inner shelf past Roosevelt Island after 3.2 ka ^{14}C BP (Conway et al., 1999). For this view of WAIS retreat chronology to be correct there must have been deposition of all three GZWs within a relatively short span of 7.8 kyr. This timeframe corresponds to the onset of retreat from the outer shelf at 11 ka ^{14}C BP and decoupling of grounded ice around the flanks of Roosevelt Island at 3.2 ka ^{14}C BP. For this hypothesis to be valid large sediment volumes of the three GZWs there must have been deposited in a short span of time.

Bart and Cone (2012) proposed an alternate interpretation of the near surface GZW stratigraphy. In their view, the Gray Unit, i.e., the youngest GZW within the

Glomar-Challenger-Basin paleo trough was dated to have been deposited just prior to the peak of the LGM. Their radiocarbon dates were obtained from presumably *in situ* forams isolated from diamict sediment deposited on the surface of the Gray Unit GZW foreset within Glomar Challenger Basin. Logic dictates that if the youngest middle shelf GZW was deposited prior to the LGM, then the older outer shelf GZWs, i.e., the Brown, Red and Purple Units, must correspond to deposition during previous glacial maxima prior to the LGM (i.e., MIS 4, MIS 6, MIS 8, or MIS 10). These two interpretations of how the timing of GZW deposition relates to WAIS grounding line translations during the Quaternary are incompatible.

With the inherent uncertainty of whether forams dated by Bart and Cone (2012) are *in situ* versus reworked; Bart and Owolana (2012) used an alternative strategy to test the chronology that Bart and Cone (2012) favored. Bart and Owolana (2012) used two end-member sediment flux values based on their assessments of the modern flux at the Whillans Ice Stream (Anandrakrishnan et al., 2007). Both end-members were larger than the modern flux because the drainage area was significantly larger when the WAIS was grounded on the outer shelf. A retreat mode flux used the same yield as the modern drainage because they viewed the modern system exists in the peak of an interglacial. The advance-mode flux used a lower yield because during the colder glacial, ice-sheet flow is slower and erosion rates are lower.

The retreat-mode flux yielded a 1.47 kyr duration for the Gray Unit grounding event. This duration is consistent with the conventional view of post-LGM deposition proposed by Conway et al. (1999). Given the slower sediment flux for glacial advance mode of deposition, the Gray Unit sediment volume would have required a longer duration. On this basis, Bart and Owolana (2012) proposed that the Gray Unit grounding event duration would have been 147.34 kyr. Bart and Owolana (2012) concluded that both views for the Gray Unit GZW deposition should be considered feasible. This view is not consistent with the conventional view of ice sheet retreat proposed by Conway et al. (1999).

The objective of this study is to investigate the duration of the Brown Unit within the Glomar-Challenger Basin (GCB), Whales-Deep Basin (WDB), and Little America Basin (LAB) paleotroughs. In conjunction with Bart and Cone (2012), Bart and Owolana (2012), and Bowles (2013), the information on the Brown Unit grounding event duration will aid in compiling the durations of all three GZWs within eastern Ross Sea. The synthesis of these data will help determine how the near surface stratigraphy relates to WAIS grounding line translations during the Quaternary. More specifically, the hypothesis of a post-LGM depositional timeframe of the Brown Unit will be tested using the methods employed by Bart and Owolana (2012). In their preliminary analysis of the Brown Unit, Bart and Owolana (2012) proposed that the Brown Unit has an average thickness of 50 m and an area of 1.25×10^{10} m^2 in Glomar Challenger Basin (Bart and Owolana, 2012). On this basis, the volume was estimated to be 6.25×10^{11} m^3. Using a retreat mode flux, the duration of the Brown Unit grounding event was calculated to be 2.5 kyr (Bart and Owolana, 2012). A depositional timeframe of 2.5 kyr for the Brown GZW is in good agreement with the post LGM timeframe proposed by Conway et al. (1999) but when combined with their preliminary durations of the underlying Red Unit and overlying Gray Unit, the total duration of post-LGM sedimentation exceeds the maximum amount of time within the post-LGM. Bart and Owolana (2012) focused on the Gray Unit and their estimation of the Brown and Red Unit volumes was not based on detailed mapping. This study specifically investigates the Brown Unit grounding event duration via a more comprehensive mapping of the unit.

Methods

Methods employed within this investigation of the Brown unit GZW follow closely to that used by Bart and Owolana (2012). The top and base of the Brown GZW unit was correlated and interpreted across the three Eastern Ross Sea paleotrough basins using seismic data (Figure 1) that consisted of five single-channel seismic surveys, M89, PD90, NBP94, NBP95 and NBP08 . The M89 dataset was shot with a sparker source and the PD and NBP datasets used a generator injector airgun source. All seismic lines were plotted to have 100ms in TWTT on the Y-axis at 2in. This ensured that all lines from the various datasets were at equal scale and that different resolution of data sets to be easily compared to minimize over or under interpreting observations from seismic data set to seismic data set. The thickness in milliseconds was calculated from the top and base of the Brown Unit. Time-structure contour maps of the top and base along with an isopach were then hand contoured and digitally scanned for import into Adobe Illustrator CS5. From the five seismic datasets, interpretations of the Gray, Brown, Red and Purple seismic units were made for 18 seismic lines. Line drawings of these interpretations were transferred by hand to mylar. The mylars were digitally scanned and imported to Adobe Illustrator CS5. The line drawing interpretations were digitized in Adobe Illustrator CS5.

Area and Volume Calculations of the Brown Unit

Area calculations were obtained through a combination of Adobe Illustrator CS5 and Paint.NET (digital photo editing software) software. In Adobe Illustrator CS5, a grid with box dimensions each equivalent to an area of 3,000 m by 3,000 m on the seismic base map was created. With this grid, the digitized and scaled version of isochron contour map was converted to a high resolution jpeg image at 200 DPI. The jpeg image was imported to Paint.NET software. In Paint.NET, the length and width of the 3,000 by 3,000 meter boxes were measured in pixels. Within Paint.NET, the highlight tool was used to assign different colors to the regions bound by adjacent contours. Paint.NET generates the number of square pixels for each of the color-assigned contoured intervals. The known relationship between square pixels and grid box area was then used determine the square area for each contour interval of that thickness using the equation below.

$$\frac{Area_{box}\,(pxl^2)}{3{,}000m \times 3{,}000m} = \frac{Area_{contour}(pxl^2)}{X_{Contour\ area}(m^2)} \qquad (1)$$

The area for each contour interval of the isochron map was then multiplied by medium thickness for each interval. The medium thickness in TWTT was converted to depth using a velocity of 1750 m/s from Cochrane et al. (1995) as shown in Equation 2

$$T = \frac{Vt}{2} \qquad (2)$$

where T is the sediment thickness (meters), V is the sediment velocity of 1,750 (m/s) and t is the two-way travel time (seconds).

The total volume was calculated by adding all contour interval sediment volumes, each increment of volume corresponding to the product of the contour interval thickness times the number of pixels converted to map area. The sum of all contour interval volumes resulted in the net volume for the mapped Brown GZW unit.

Brown GZW Duration

The flux and yield used to estimate the duration of the Brown Unit followed the strategy described by Bart and Owolana (2012). They utilized the Whillans Ice Stream

GZW to deduce modern sediment yield and flux. The modern yield and flux was adjusted because when the WAIS was grounded on the outer shelf, the drainage area was significantly larger than the modern drainage area. A second adjustment was made because yield and flux varies during the glacial cycle. Modern flux is taken to represent yield values during ice sheet retreat because the modern interglacial occurs within the peak of the interglacial cycle. Yield and flux are lower during glacial periods when the ice is colder and less meltwater exists. These lower yield/flux rates are consistent with sediment yield and flux estimated for the peak glacial maxima versus the higher yield/flux measured for modern systems (Elverhoi et al., 1998, Hallet et al., 1996, Koppes and Montgomery, 2009, Fernandez et al., 2011). Within interglacial phases, we assume that the measurable value of sediment yield is on the order of two magnitudes greater than that existing in glacial periods by means of faster moving ice streams during warmer phases (Koppes and Montgomery, 2009, Fernandez et al., 2011).

The Whillans Ice Stream has a modern flux of 200m^3/m/a. The modern GZW at its marine terminus is believed to have taken 1,000 years to construct (Anandrakrishnan et al., 2007). The modern 3D sediment flux ($Q_{S(3D))}$) of the Whillans Ice Stream was calculated to be 5.5×10^7 m^3/a by Bart and Owolana (2012). This modern flux is the total quantity of sediment that leaves the drainage basin to enter the receiving base per unit of time (Bart and Owolana, 2012).

Using the modern 3D flux and the modern area of the Whillans Ice Stream drainage basin area (Figure 6), Bart and Owolana (2012) calculated the average sediment yield using Equation 3:

$$S(m^3/m^2/a) = \frac{Q_{3D}(m^3/a)}{Area_{drainage}(m^2)} \qquad (3)$$

where S is yield and Q_{3D} is 3D sediment flux.

The modern ice drainage basin for the Whillans Ice Stream is composed of igneous, metamorphic and sedimentary rock types. According to Schlunegger et al. (2001), metamorphic rocks produce a yield that is 30% less than that of the sedimentary rock. Igneous rock produces a yield 25% lower than sedimentary rock. Equations 4 and 5 are used to account for differences in yield depending upon the rock types presumed to exist within the drainage basin

$$S_m = 0.7 \times S_s \qquad (4)$$

$$S_i = 0.75 \times S_s \qquad (5)$$

where S_m is the yield for the drainage basin composed of metamorphic basement rock and S_s is the yield for the drainage basin underlain by sedimentary rock and S_i is the yield for underlying igneous rock. Using equations 3 and 4, Bart and Owolana (2012) calculated S_s to be 2.659 x 10^{-4} $m^3/m^2/a$ and S_m to be 1.862 x 10^{-4} $m^3/m^2/a$ (Table 1).

Because the mapping showed that the Brown Unit exists in Whales-Deep and Little-America basins, the drainage area used to calculate the flux was considerably larger than that utilized by Bart and Owolana (2012). The paleo drainage basin for the Brown Unit includes Glomar-Challenger, Whales-Deep, and Little-America basins. This corresponds to areas A, B, C, D, E, F, and G on Figure 6. The area of the larger paleo drainage basin was calculated using data from Rignot et al. (2012) and Paint.NET software (Table 1).

Table 1. Drainage basin areas, retreat-mode yields and flux, and advance-mode yields and flux. A) Modern drainage basin areas that converge to Glomar Challenger Basin (GCB), Whales Deep Basin (WDB), and Little America Basin (LAB) (see Figure ?). The total drainage area is divided into what rock type underlies the grounded ice for yield estimates with S= sedimentary rock, M=metamorphic rock, and V=volcanic rock. B. Drainage areas calculated using data from Rignot et al. (2002) and Adobe illustrator and paint.net software. C. Retreat-mode yields, S_s, S_m, and S_i, (for sedimentary, metamorphic, and igneous rocks, respectively) and associated retreat-mode flux, Q_{3DR}. D) Advance-mode yields and associated advance-mode flux, Q_{3DA}. The last row for column B is the total paleo drainage area for the Brown GZW. The last row for column C and D is the total flux contributions of all the areas delivering sediment to GCB, WDB, and LAB during the Brown grounding event.

A. Map region (figure 6)	B. Drainage Area (m^2)	C. Retreat-mode yield and flux				D. Advance-mode yield and flux			
		S_s ($m^3/m^2/a$)	S_m ($m^3/m^2/a$)	S_v ($m^3/m^2/a$)	Q_{3DR} (M^3/a)	S_s ($m^3/m^2/a$)	S_m ($m^3/m^2/a$)	S_v ($m^3/m^2/a$)	Q_{3DA} (M^3/a)
A/B_s	$1.42 \pm .01 \times 10^{11}$	$2.66 \pm 0.24 \times 10^{-4}$	-	-	$3.75 \pm 0.34 \times 10^{7}$	$2.66 \pm 0.24 \times 10^{-6}$	-	-	$3.75 \pm 0.34 \times 10^{5}$
A/B_m	$8.49 \pm 0.05 \times 10^{10}$	-	$1.86 \pm 0.17 \times 10^{-4}$	-	$1.75 \pm 0.16 \times 10^{7}$	-	$1.86 \pm 0.17 \times 10^{-6}$	-	$1.75 \pm 0.16 \times 10^{5}$
C_s	$1.33 \pm 0.01 \times 10^{11}$	$2.66 \pm 0.24 \times 10^{-4}$	-	-	$3.52 \pm 0.32 \times 10^{7}$	$2.66 \pm 0.24 \times 10^{-6}$	-	-	$3.52 \pm 0.32 \times 10^{5}$
C_m	$1.99 \pm 0.01 \times 10^{10}$	-	$1.86 \pm 0.17 \times 10^{-4}$	-	$3.70 \pm 0.33 \times 10^{6}$	-	$1.86 \pm 0.17 \times 10^{-6}$	-	$3.70 \pm 0.33 \times 10^{4}$
D_s	$1.27 \pm 0.01 \times 10^{11}$	$2.66 \pm 0.24 \times 10^{-4}$	-	-	$3.37 \pm 0.28 \times 10^{7}$	$2.66 \pm 0.24 \times 10^{-6}$	-	-	$3.37 \pm 0.30 \times 10^{5}$
D_v	$1.54 \pm 0.01 \times 10^{10}$	-	-	$1.99 \pm 0.18 \times 10^{-4}$	$3.06 \pm 0.28 \times 10^{6}$	-	-	$1.99 \pm 0.18 \times 10^{-6}$	$3.06 \pm 0.28 \times 10^{4}$
E_s	$8.31 \pm 0.05 \times 10^{10}$	$2.66 \pm 0.24 \times 10^{-4}$	-	-	$2.21 \pm 0.20 \times 10^{7}$	$2.66 \pm 0.24 \times 10^{-6}$	-	-	$2.21 \pm 0.20 \times 10^{5}$
E_v	$6.78 \pm 0.04 \times 10^{10}$	-	-	$1.99 \pm 0.18 \times 10^{-4}$	$1.35 \pm 0.12 \times 10^{7}$	-	-	$1.99 \pm 0.18 \times 10^{-6}$	$1.35 \pm 0.12 \times 10^{5}$
F_s	$2.81 \pm 0.02 \times 10^{10}$	$2.66 \pm 0.24 \times 10^{-4}$	-	-	$7.47 \pm 0.67 \times 10^{6}$	$2.66 \pm 0.24 \times 10^{-6}$	-	-	$7.47 \pm 0.67 \times 10^{4}$
G_s	$1.05 \pm 0.01 \times 10^{10}$	$2.66 \pm 0.24 \times 10^{-4}$	-	-	$2.80 \pm 0.25 \times 10^{6}$	$2.66 \pm 0.24 \times 10^{-6}$	-	-	$2.80 \pm 0.25 \times 10^{4}$
G_v	$5.59 \pm 0.03 \times 10^{9}$	-	-	$1.99 \pm 0.18 \times 10^{-4}$	$1.11 \pm 0.10 \times 10^{6}$	-	-	$1.99 \pm 0.18 \times 10^{-6}$	$1.11 \pm 0.10 \times 10^{4}$
Offshore	$3.87 \pm 0.02 \times 10^{11}$	$2.66 \pm 0.24 \times 10^{-4}$	-	-	$1.03 \pm 0.01 \times 10^{8}$	$2.66 \pm 0.24 \times 10^{-6}$	-	-	$1.03 \pm 0.09 \times 10^{6}$

(Table 1 continued)

A. Map region (figure 6)	B. Drainage Area (m^2)	C. Retreat-mode yield and flux				D. Advance-mode yield and flux			
		S_s ($m^3/m^2/a$)	S_m ($m^3/m^2/a$)	S_v ($m^3/m^2/a$)	Q_{3DR} (M^3/a)	S_s ($m^3/m^2/a$)	S_m ($m^3/m^2/a$)	S_v ($m^3/m^2/a$)	Q_{3DA} (M^3/a)
SUF'	$2.35\pm 0.01 \times 10^{11}$	-	$1.86\pm 0.17 \times 10^{-4}$	-	$4.38\pm 0.39 \times 10^{7}$	-	$1.86\pm 0.17 \times 10^{-6}$	-	$4.38\pm 0.39 \times 10^{5}$
Total	1.35 ± 0.01 e10^{12}	-	-	-	$3.24\pm 0.29 \times 10^{8}$	-	-	-	$3.24\pm 0.29 \times 10^{6}$

The larger paleo drainage basin for the Brown GZW unit includes portions of Marie Byrd Land (Figure 2, Areas D, E, F, G). Marie Byrd Land is primarily composed of mid-Cretaceous plutonic basement rock including granitoids, basalts, and gabbros (Weaver et al., 1994).

Very wide ice streams are inherently unstable, and therefore can decelerate or completely stagnate for significant periods of time (Joughin et al., 2002). Stagnation can be caused by a switch from basal melting to basal freezing (Christoffersen and Tulaczyk, 2003). The modern grounding event began roughly 1000 ± 200 years ago. The Kamb Ice Stream was stagnant for the last150 ± 22.5years or ~15% of the grounding event duration (Joughin et al., 2002, Christoffersen and Tulaczyk, 2003).

However, the modern grounding event duration and ice stream stagnation duration are very difficult to quantify. Because ice streams are unstable, it is probable that the ice stream could have been stagnant over multiple intervals throughout the modern grounding event. A reasonable assumption is that the ice stream stagnation could have ranged from 15%- 30% of the modern grounding event duration with an average stagnation of 22.5 ± 7.5%.

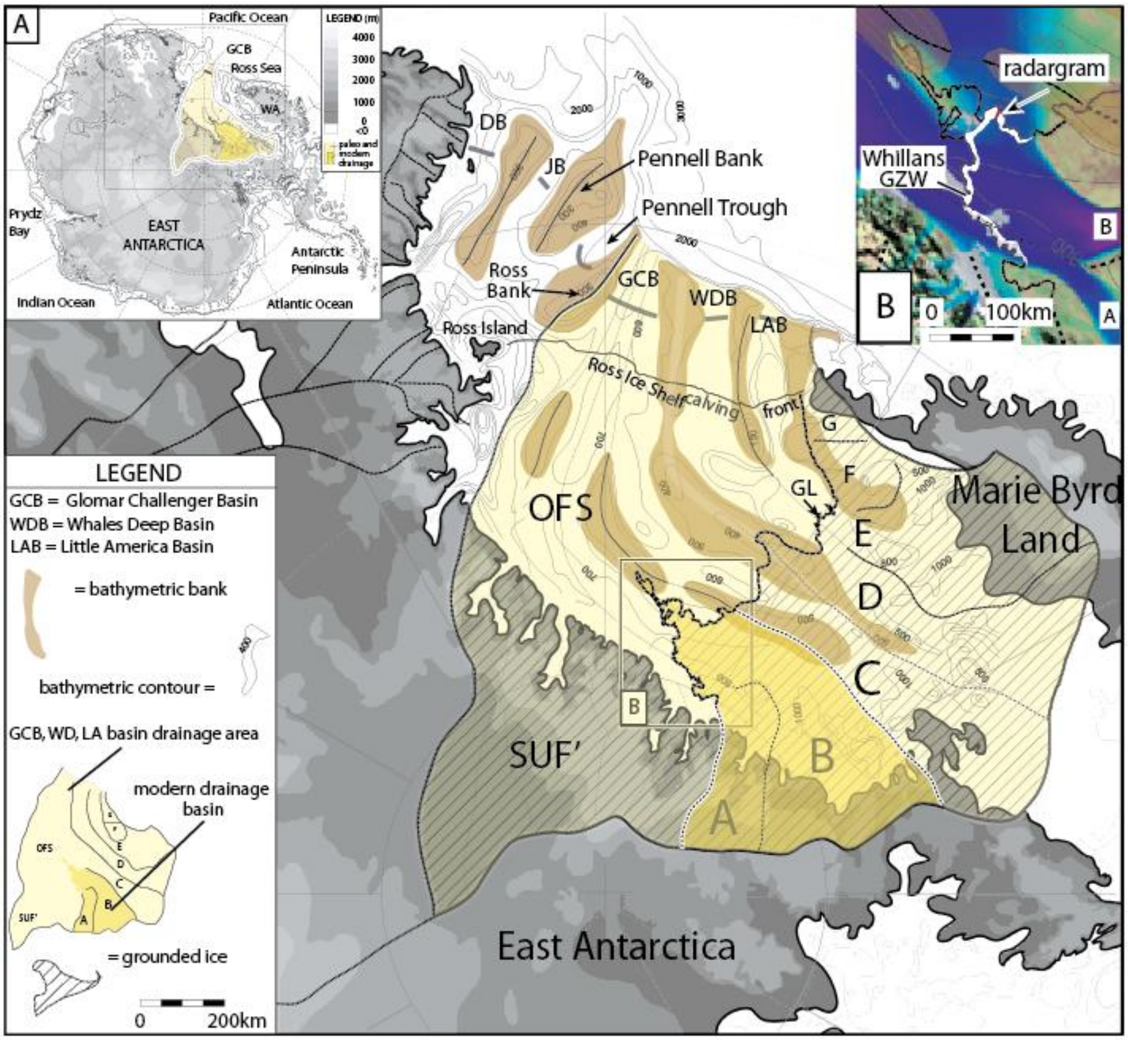


Figure 2. Eastern Ross Sea drainage basin map.

The ice stream stagnation time of 150 ± 33.8 years should be considered an absolute minimum stagnation time. The grounding event duration for the Brown Unit was calculated using Equation 6:

$$D = (V_{sed}/Q) + ((V_{sed}/Q) \times 0.15) \quad (6)$$

where D is grounding event duration in years (a), V_{sed} is sediment volume (m^3), Q is the flux (m^3/a), and 0.15 is a constant used for ice stream stagnation. The duration was calculated using modern, retreat-mode, and advance-mode fluxes.

In search for a true volume, porosity and water content of the unit could affect the calculated volume and grounding event duration of the Brown Unit. Sediment piston cores from Domack et al. (1999) describe a diamict lithology at the seafloor from the middle and outer shelf throughout the Glomar Challenger Basin and along the Hayes Bank. These samples depict the GZW sediment consisting of diamicton that is uniform in character lacking observable bioturbation structures. In >85% of the cores collected by Domack et al. (1999) in the Ross Sea, the average water content was ~30% with pore waters of marine origins in all cases. Adversely, according to Anandrakrishnan et al. (2007), the sediment inland of the Ross Sea paleotroughs has a water content of 45%. Thus within the sediment a 15% water content loss is noted as the subglacial deforming till passes the grounding line and is deposited. This is an effect of the grounded ice transitioning to a floating ice shelf, the normal force acting upon the till is no longer present and thus we interpret a release of pore waters trapped within the GZW sediment to occur.

The Brown Unit has a water content of roughly 30%, we note that this value does not affect this study's volume and grounding event duration calculations. This is due to the sediment yield, flux, and volume this study calculated accounts for both the water content and the ~15% water loss. The calculated volume of the Brown Unit determined within this study includes the water within the sediment. In addition, this study deems the sediment yields (Ss, Sm, Sv) as essentially 'effective yields' in that they account for both the sediment and water that gets transferred to the sea bed. The 'effective yields' are smaller than the 'actual yields' because the 'actual yields' don't account for the water content. In comparing the experiment's results, the yields determined within this study are smaller in contrast to sediment yields calculated using similar methodology. More specifically, they should be roughly 15% smaller due to this study's inclusion of the water content which contributes to ~15% of the calculated volume. Lastly, the paleo sediment flux calculated in this study should also be considered an 'effective flux' because it also includes the sediment and water that gets directly transferred to the sea bed. This 'effective flux' is roughly 15% less than the 'actual flux' which includes water loss to the sea. Because the calculated volume of the Brown Unit, the sediment yield, and the sediment flux all include water content within the sediment, the calculated grounding event duration for the Brown Unit (equation 6) remains the same.

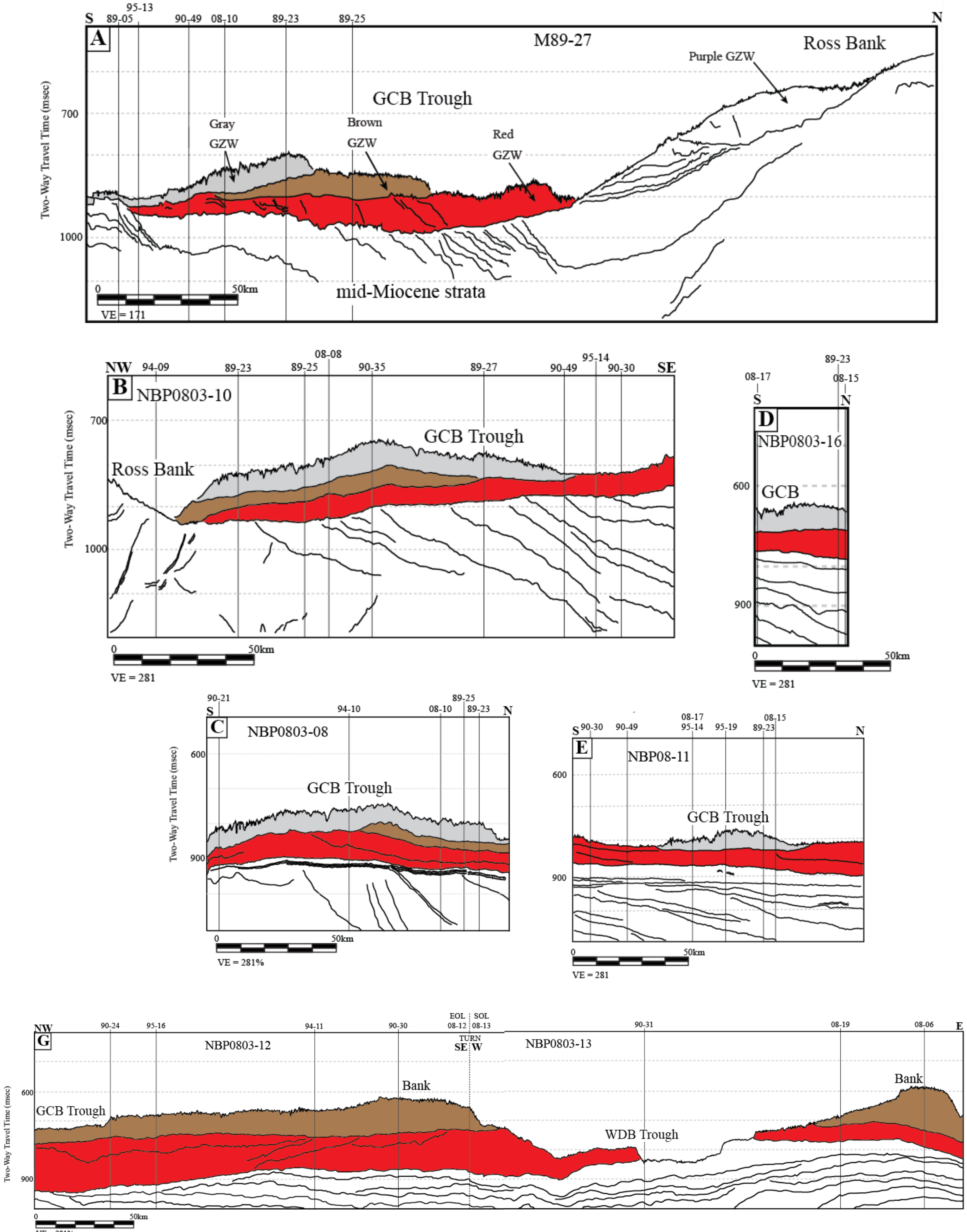
Results

Brown Unit Areal Extent

Seismic profiles show that the Brown Unit is a low-relief sediment sheet that extends from the middle and outer shelf in troughs and banks of the eastern Ross Sea (Figure 3, A-S). The top of the Brown Unit is everywhere defined by the Brown Unconformity. In places, erosion at the Brown Unconformity completely removed the Brown Unit. The thinning and/or completed erosion of the Brown Unit coincides with the locations of the Glomar-Challenger, Whales-Deep and Little-America basin paleo troughs (Figure 3, A-S). Because of these stratal arrangements, the Brown Unconformity defines the top of the Red Unit along the axes of the modern basins (Figure 3; G, H, I, R). Along the Hayes and Houtz banks a minute presence of internal reflectors is observed within the Brown Unit GZW. This is in stark contrast to the Red Unit where internal reflectors are observed throughout the entirety of the study area. The time-structure contour maps of the Brown Unit thickness and upper and lower bounding surfaces show the unit's limits and the topography that existed prior to and after the culmination of the Brown Unit grounding event (Figures 3-5). The mapping shows that the Brown Unit has appreciable thickness in the Glomar Challenger Basin but that the unit is also thick at the adjacent bank to the east. As mentioned earlier, this is in contrast to Whales Deep and Little America Basin, where the Brown Unit has been completely eroded. In other words, the Brown Unit is thick in the bathymetric highs separating the basins. The Brown GZW extends 291 km in the North/South dip direction.

Figure 3. Seismic line interpretations

(Figure 3 continued)



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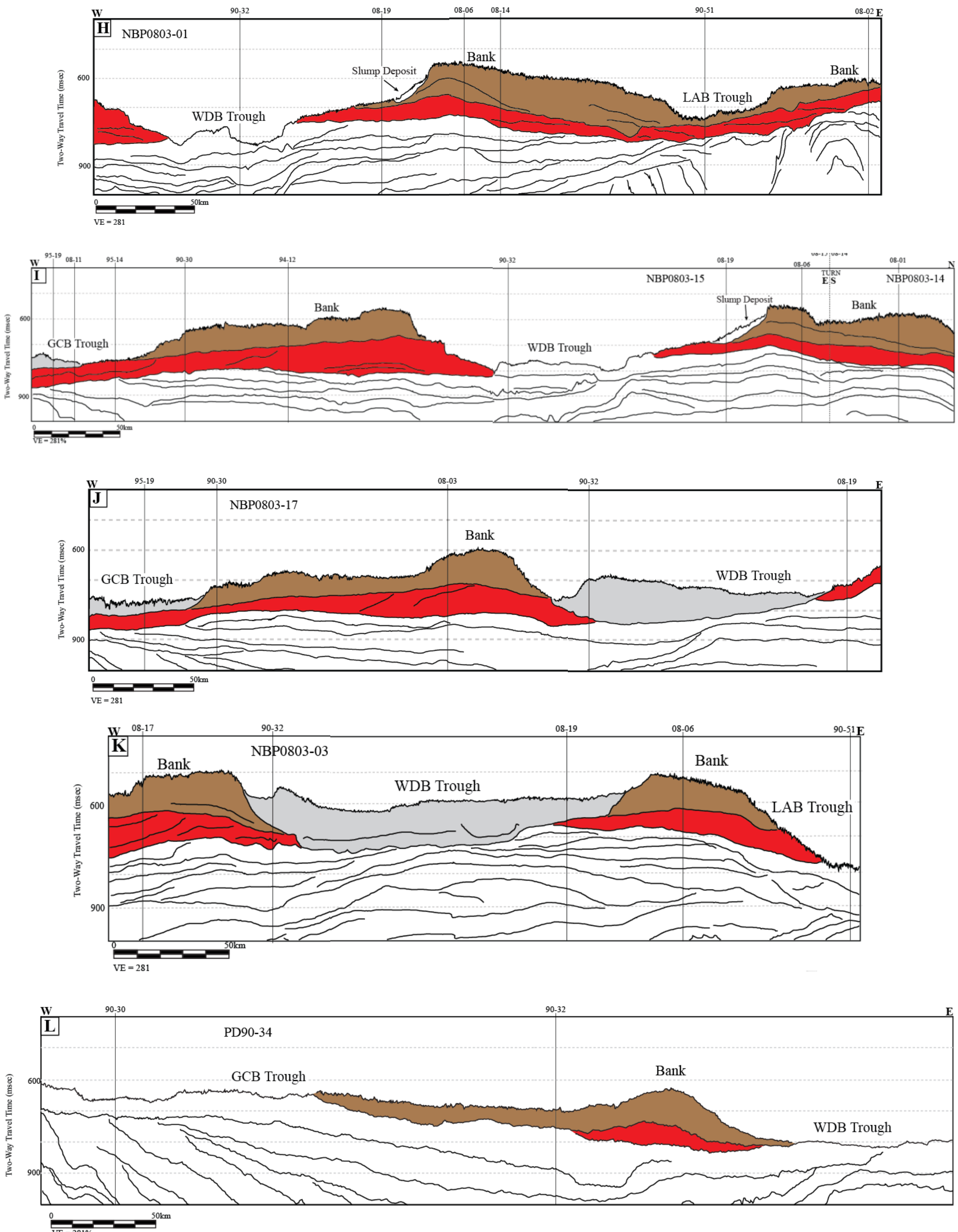

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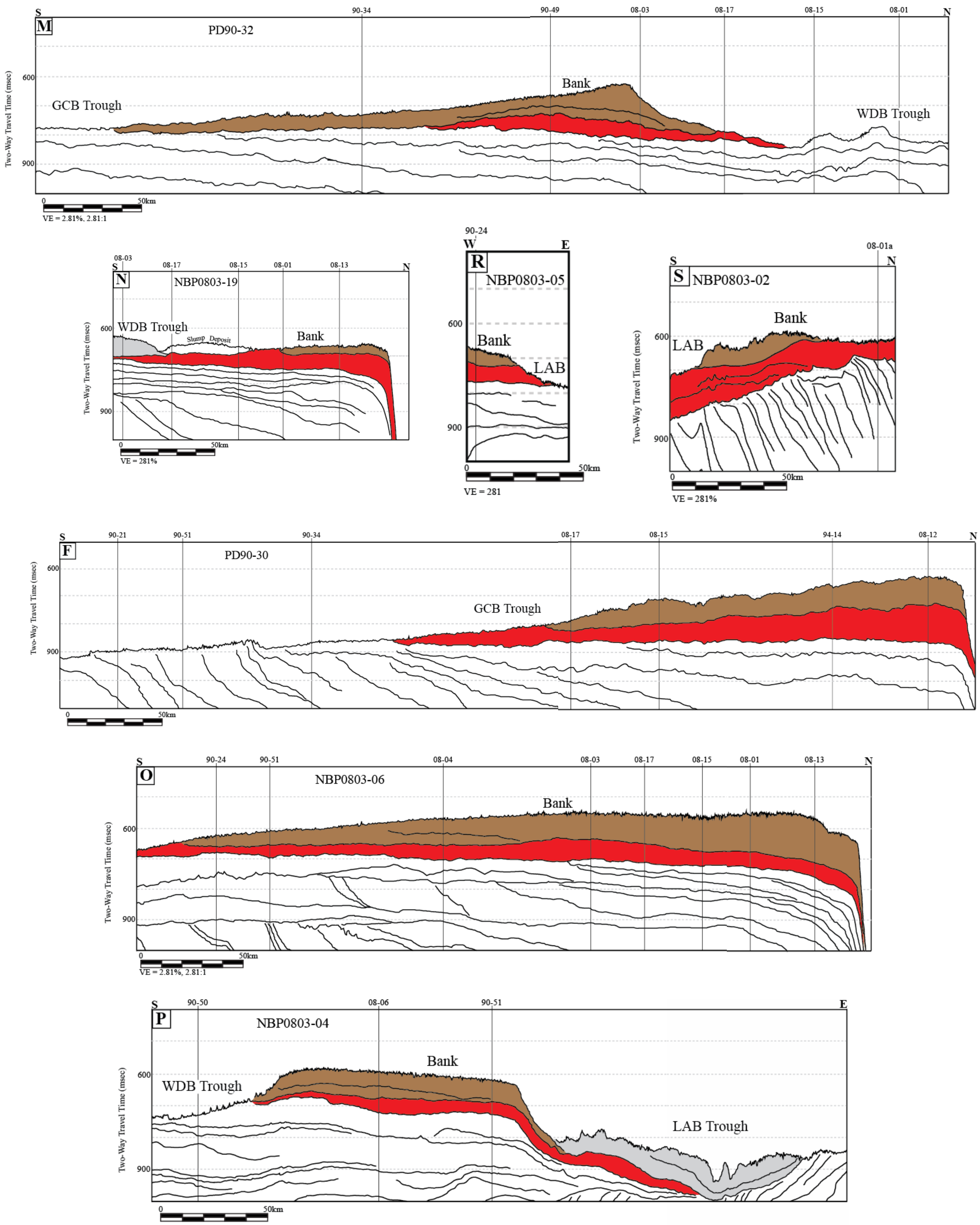

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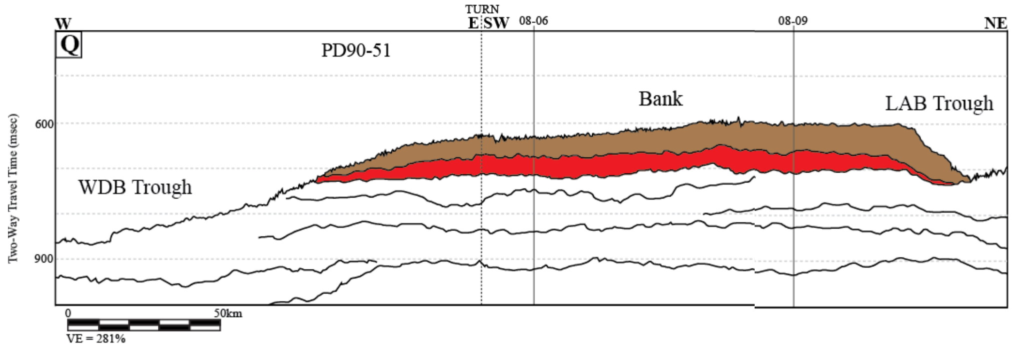


The landward limit is 33 km north of the Ross Ice Shelf calving front and the basinward limit is at the shelf edge. The maximum extent of the stratigraphic unit on the lower slope was not investigated because the seismic data used in this study is confined to the outer shelf and upper-most slope. In the east-west direction the Brown Unit is 465 km across. The zones in which the Brown Unit is eroded from the paleo troughs are ~65 km across at the Whales Deep and Little America basins. The southern limit has a curvilinear trend. The most-landward extent coincides to where the Brown Unit is thick at the modern seafloor banks.

Volume and Grounding Event Durations

The isochron contour map of the Brown Unit illustrates the unit thickness across banks and troughs of eastern Ross Sea (Figure 6). The thickness of the Brown Unit ranges from 0 msec (0m) to 170 msec (~144 m) with the average thickness of 57 m. Using an average acoustic velocity of 1,750 ± 200 m/s, the Brown Unit sediment volume is $1.45 \pm 0.03 \times 10^{12}$ (Table 2). The duration of the Brown grounding event was estimated using a retreat-mode flux (Q_{3DR}= $3.24 \pm 0.29 \times 10^{8}$ m^3/a), and an advance-mode flux (Q_{3DA}= $3.24 \pm 0.29 \times 10^{6}$ m^3/a) (Table 2).

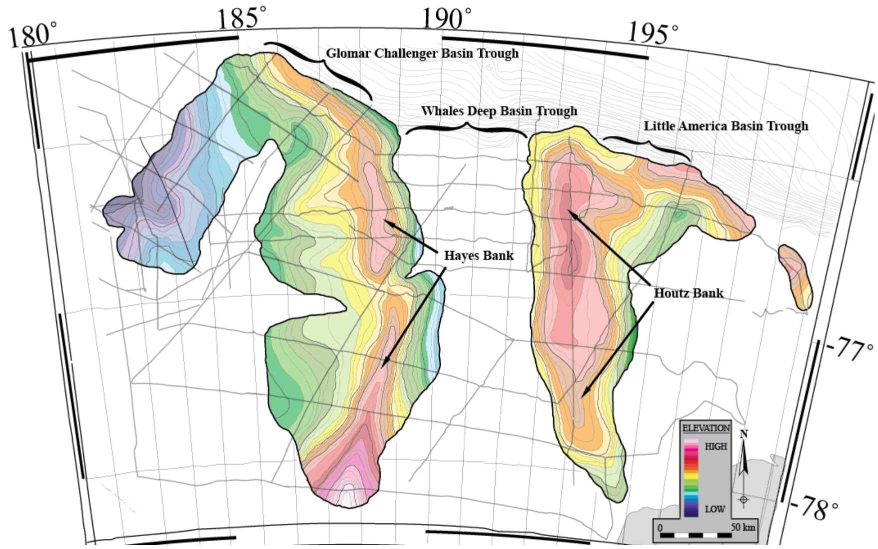


Figure 4. Time-structure contour map of the top of the Brown Unit.

Using the modern flux, the duration of the grounding event was estimated to have been 30,213 years (Table 2, column C). Using the retreat-mode flux, the grounding event duration was estimated to have been 5,128 ± 1,000 years (Table 2, column D). Using the advance-mode flux, the Brown Unit grounding event was estimated to have been 512,886 ± 100,000years (Table 2, column E).

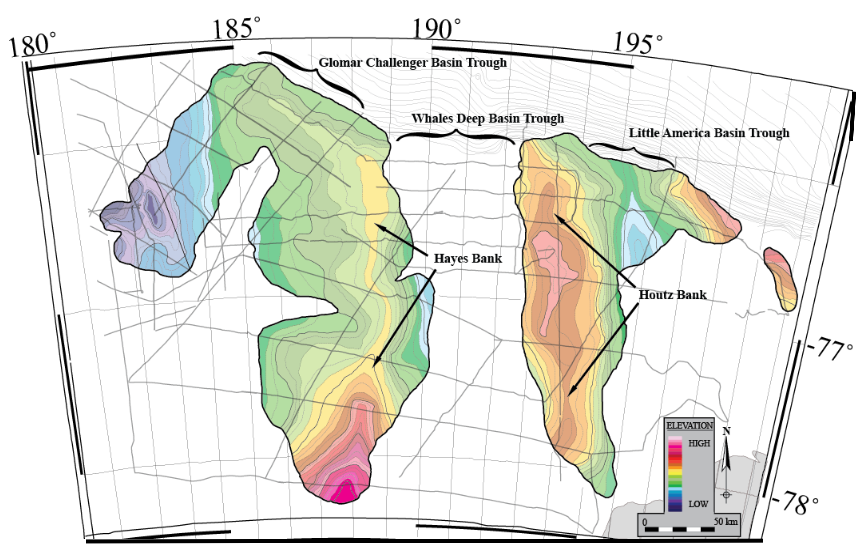


Figure 5. Time-structure contour map of the base of the Brown Unit.

Table 2. Grounding event durations for the Gray, Brown, and Red GZWs including durations with modern flux, retreat-mode flux, and advance-mode flux. B) GZW volumes as calculated using isopach maps. C) Grounding event duration using modern flux (Q_{3DM}) at Whillans Ice Stream. D) Grounding event duration using retreat-mode flux (Q_{3DR}) for GCB, WDB, and LAB. E) Grounding event duration using advance-mode flux (Q_{3DA}) for GCB, WDB, and LAB. GCB= Glomar Challenger Basin, WDB= Whales Deep Basin, and LAB= Little America Basin.

A. GZW Name	B. GZW Volume (m^3)	C. GE duration w/ retreat-mode flux (yr)	D. GE duration w/ advance-mode flux (yr)	A. GZW Name
		Q_{3DR}= 3.24± 0.29 x 10^8 m^3/a	Q_{3DA}= 3.24± 0.29 x 10^6 m^3/a	
Gray	3.57± 0.07 x 10^{11}	1,477± 312	147,770± 31,268	Gray
Brown	1.45 ± 0.03 x 10^{12}	5,128± 1,085	512,886± 108,526	Brown
Red	2.12 ± 0.06 x 10^{12}	7,507± 1,588	750,694± 158,847	Red
All GZWs	3.92 ± 0.08 x 10^{12}	14,112± 2,986	1,390,350± 294,198	All GZWs

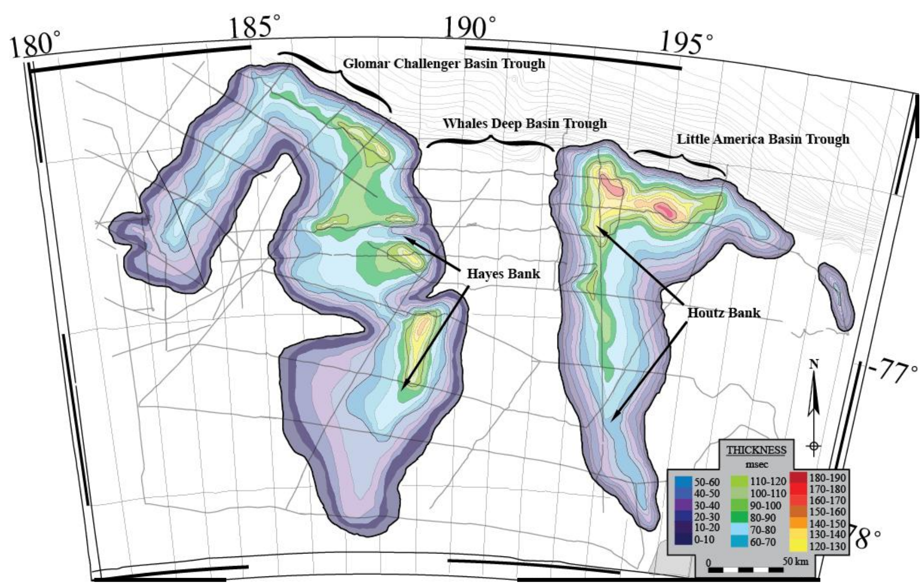


Figure 6. Isochron of the Brown Unit.

Discussion

Estimate of the retreat-mode duration for the Brown Unit grounding event

The duration estimated using the modern flux is eliminated from further consideration because the data show that the Brown Unit is an ice contact deposit. In other words, the WAIS was grounded on the outer shelf when the Brown Unit formed. The 5.1-kyr duration estimated using the retreat mode flux is short enough that the unit could have been deposited during the post-LGM time frame even when combined with the 1.47 kyr retreat-mode duration (Bart and Owolana, 2012) estimated for the Gray Unit GZW. The 5.1-kyr estimated duration is longer than the 2.4 kyr Brown Unit grounding event duration estimated from Bart and Owolana (2012). The longer duration presented here is a better estimate because it is based on a more detailed assessment of volume.

These retreat-mode durations for the Brown and Gray units represent ~60% of the time since the onset of post-LGM retreat. The recent estimate for the Red Unit retreat-mode duration, 7.5 kyr (Bowles, in prep.), in combination with the retreat-mode durations for the Brown and Gray Unit exceed the total time between the onset of retreat and southward translation of grounded ice past Roosevelt Island. This precludes the possibility that all three units can be assigned to the post-LGM. Within the context of these retreat-mode durations, the data permit that the Red Unit is the LGM deposit, and that the Brown and Gray Units represent two post-LGM grounding events.

The later considerations are consistent with the tenets presented by Conway et al. (1999), i.e., that the WAIS retreated gradually from eastern Ross Sea. It is important to keep in mind that the volume for the Brown Unit is a minimum. For example, the erosion of the Brown Unit from the Whales Deep and Little America basins suggests that this sediment may have bypassed the shelf and been deposited on the slope or basin floor. This possibility cannot be precisely evaluated because the data used in this study do not extend to past the upper-most slope. It does not appear that significant upper-slope depocenters, i.e., trough-mouth fans, were constructed during the Brown Unit grounding event. Multichannel seismic data from ANTOSTRAT (1995) suggest that Quaternary strata have appreciable thickness on the slope and adjacent continental rise. The lower resolution of the multichannel data does not permit a one-to-one correlation of the Brown Unit described in this study to reflectors seen on multichannel data. In other words, it is not clear if the expanded section seen on the multichannel data should be assigned to the Brown Unit or some older stratigraphic interval. Nonetheless, it is highly likely that some sediment was transported to the slope environment when the WAIS was grounded at the shelf edge during the Brown Unit grounding event (Bart and Anderson, 1995).

The relatively short retreat-mode duration (5.128 ky) of the Brown unit GZW opens the possibility that the Brown Unit (and the overlying Gray Unit) could have been deposited within a post-LGM timeframe (11 ky) but only if the Red Unit represents the LGM deposit. This is because the 7.5 kyr retreat mode duration of the Red Unit estimated by Bowles (2013) in combination with the durations for the Brown Unit (this study) and Gray Unit (Bart and Owolana, 2012) exceed the duration of the post-LGM time.

These calculated durations must also be considered minimum durations. For example, according to Alley et al. (1989), erosion and sediment yield in the drainage basin is highest within the boundaries of ice streams. The sediment yields (Ss, Sm, and Sv) calculated by Bart and Owolana (2012) and by this study, represent the high sediment yield within the ice streams. However, this study applies these high yields to the entire LGM drainage basin when, in fact, they most accurately represent the yields within the modern drainage basin for the Whillans Ice Stream (Figure 6). The high velocity ice streams represent 17.7% of the modern drainage basin and 2.4% of the LGM drainage basin. Even though the LGM drainage area is roughly 7 times larger than the modern drainage area, the boundaries of the ice streams were not larger during the LGM. Because of this, the sediment flux for the Brown Unit and the subsequent grounding event duration for the Brown Unit must be considered minimum values.

The Brown Unit grounding event duration estimated for the retreat-mode flux probably represents a highly conservative estimate. The large areas of the shelf from where the Brown Unit is removed shows that it originally contained a large volume that is not included in the grounding event duration calculation. For this reason, the possibility that the Brown Unit is a post-LGM deposit is excluded.

Using the advance-mode flux estimate, deposition of the Red Unit (Bowles, 2013), Brown Unit (this study), and Gray Unit (Bart and Owolana, 2012) would take ~1.4 Myr. This estimated duration is obviously does not support the conventional view of how the near-surface units relate to post-LGM grounding line translations as envisioned by Conway et al. (1999).

Estimate of the advance-mode duration for the Brown Unit grounding event

Our duration calculations leave two end-member possibilities to explain how the Brown Unit grounding event relates to WAIS grounding line translations. Both possibilities concern advance-mode flux. In the first possibility, the Brown Unit represents the culmination of erosion and deposition during the last glacial cycle. In the second possibility, the Brown Unit represents the culmination of several glacial interglacial cycles.

The 512-kr advance-mode duration estimate for the Brown Unit is far longer than the duration of the last glacial cycle. For this reason, the possibility that the Brown Unit was deposited in association with the last glacial cycle, i.e., between MIS 5e and MIS2, is rejected. The long duration instead is consistent with the second end-member possibility, i.e., that the Brown Unit represents an amalgamation of erosion and deposition during several glacial cycles.

Outer Shelf Progradational Model

The sequence of the three back stepping GZW units in the Eastern basins of the Ross Sea are conventionally interpreted as being till deltas deposited in an overall progradational fashion. For this view to be correct, the grounding line of the WAIS had to migrate landward after each grounding event and then re-advance basinward. Within this context, the LGM advance began at MIS5e, the peak of the last interglacial. At this time, the consensus view is that the WAIS must have occupied a grounding line configuration similar to that existing presently. Following this line of reasoning, the WAIS would have taken 100 ky to advance across the 1,200 km distance from the current grounding line to the eastern Ross Sea shelf edge. During the subsequent transition to the current interglacial, the WAIS retreated from the shelf edge to the modern grounding line. This conceptual model thus permits a thought experiment involving estimates for the average rate of grounding line advance and retreat during the transitions from peak glacial to peak interglacial and peak glacial to peak interglacial, respectively.

As noted above, the WAIS would have advanced 1200 km as grounding line moved from a peak interglacial to peak glacial configuration. In the post-LGM time, the mapped extent of the Red Unit (Bowles, in prep.) requires that the WAIS retreated 320 km. This distance corresponds to the landward most extent of the Red Unit (Bowles, 2013).The WAIS would have then re-advanced 320 km to the shelf edge to deposit the Brown Unit. The end of the Red Unit grounding event would have been followed by a 285 km retreat of the WAIS. The minimum retreat distance corresponds to the landward-most limit of the Brown Unit. The ice sheet would have then re-advanced 285 km and following the culmination of the Brown grounding event, the WAIS would have retreat 185 km and then subsequently advanced by this amount during the Gray Unit grounding event. Subsequent to the culmination of the Gray Unit grounding event, the WAIS would have retreated 1,015 km to the present modern grounding line location. Using this model, the grounded WAIS would have been in advance mode of a total distance of 790 km. The WAIS would have been in retreat mode for a total distance of 1,880 km. Utilizing data presented Conway et al (1999) and by Domack et al. (1999) the average rate for post-LGM retreat of the WAIS is 8.6 km per year. This requires that the WAIS would have been in retreat for 16.16 kyr of elapsed time if the WAIS experienced these grounding line translations. An average advance rate of 0.0439 km/yr indicates that it would have taken 34,177 ky of elapsed time for the WAIS complete the advance-mode grounding line translation outlined above (Table 3, Figure 7).

In addition, this thought experiment demonstrates that the WAIS could not have experience the waxing and waning that the post-LGM backstepping interpretation of the GZW stratigraphy would require. It is unlikely that the post-LGM grounding line translations were sufficiently more rapid than the average rates we outlined for significant intervals of time because this would require major changes in mass balance (Pollard and DeConto, 2009). For example, faster advances of the WAIS would require that mass accumulation of the ice sheet was significantly higher, but numerical climate models predict that accumulation rates were lower than modern rates during glacial periods because the climate was colder.

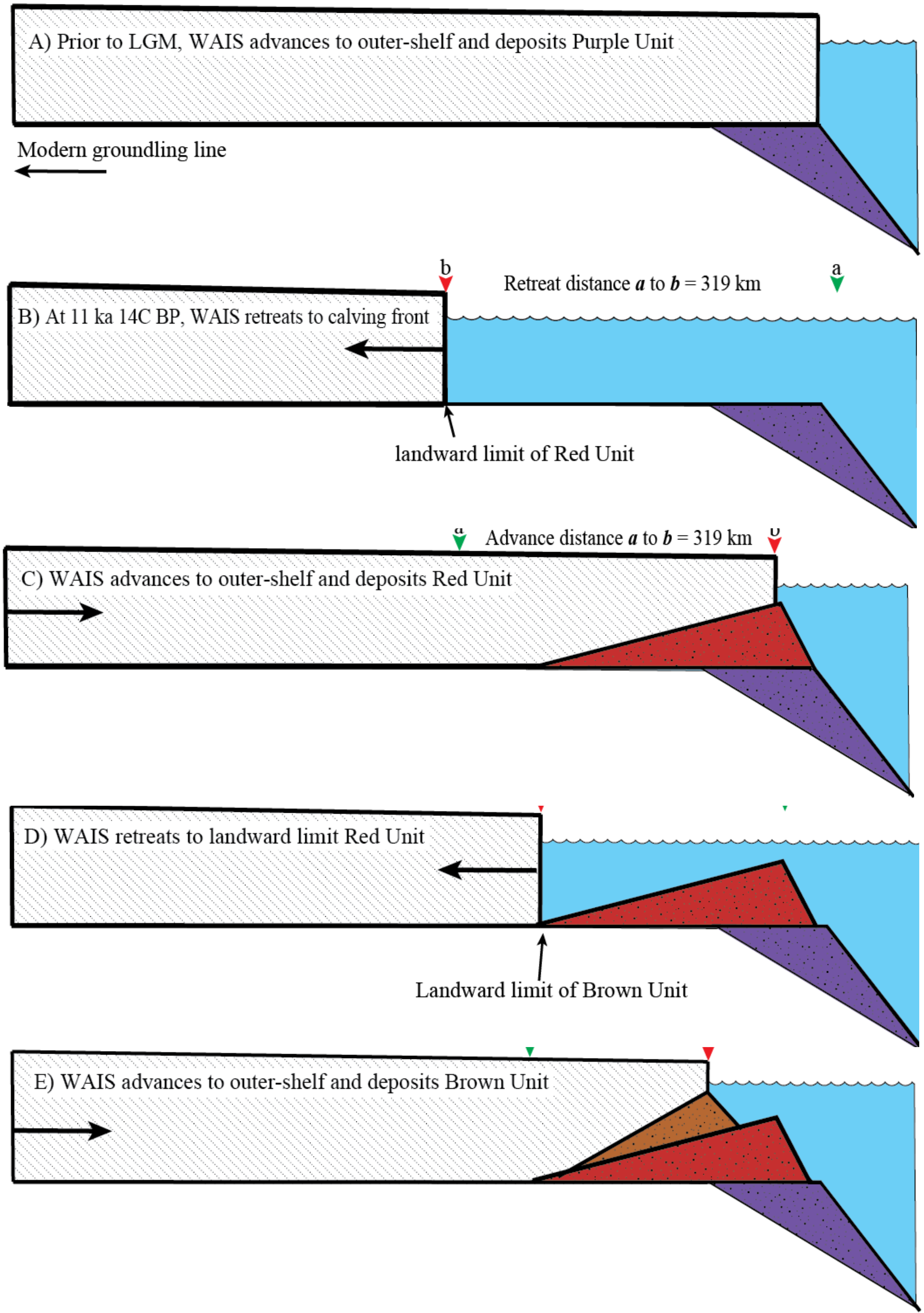
Table 3: Progradational model WAIS grounding line translation durations including retreat, advance, and total durations. A) Grounding line translation modes including advance and retreat modes. B) Grounding line translation distance (km). C) Grounding line translation duration using a retreat rate =8.6 km/yr (from Conway et al., 1999, and Domack et al., 1999). D) Grounding line translation duration using an advance rate = 0.0439 km/yr (From Emselie et al., 2007). E) Total grounding line translation duration for the progradational model. F) Grounding line translation duration for the Brown GZW Unit, refer to Figure 7-E and 7-F.

A. Grounding line translation mode	B. Grounding line translation distance (km)	C. Duration (yr) using retreat rate= 8.6± 1.15 km/yr	D. Duration (yr) using advance rate= .0439± 0.008 km/yr	E. Total duration (yr) for progradational model	F. Duration (yr) for Brown GZW Unit
Advance-mode	790± 40	-	18,018± 3,670	-	6,492±1,298
Retreat-mode	1,879± 94	16,159± 3,231	-	-	2,356±471
Total	2,669± 133	-	-	34,177± 1,784	8,848±1,769

Basinward dipping reflections within the Red Unit are interpreted as prograding foresets (Bowles, in prep.). Fewer surfaces were observed in the Brown (this study) and none within the Gray Unit (Bart and Owolana, 2012). such. On the bases of the overall similarity of the Brown and Red Unit extent and upper surface geometry, the Brown Unit is interpreted as a progradational deposit.

Figure 7. WAIS Progradational Model. Eight stage conceptual progradational models showing the sequences of WAIS advances and retreats required to deposit the back stepping GZWs (Red, Brown, and Gray Units). A) Prior to the LGM, the Purple GZW was deposited as the WAIS advances from the modern grounding line to the outer shelf. This advance occurs over a 100 ky period from MOIS5e to MOIS2. B) The ice sheet remains at the outer shelf until 11 ka ^{14}C BP when it begins its 319 km retreat to the calving front. C) The WAIS re-advances to the outer shelf and deposits the Red GZW Unit (a 319 km grounding line translation). D) The ice sheet then retreats to at *least* the landward limit of the Red GZW (285 km). E) The WAIS then advances to the outer shelf deposits the Brown GZW (285km). F) The WAIS retreats to at *least* the landward limit of the Brown GZW (274 km). G) The ensuing ice sheet advance deposits the Gray GZW on the middle shelf (186 km). H) The WAIS retreats all the way to the modern grounding line (1000 km).

(Figure 7 continued)



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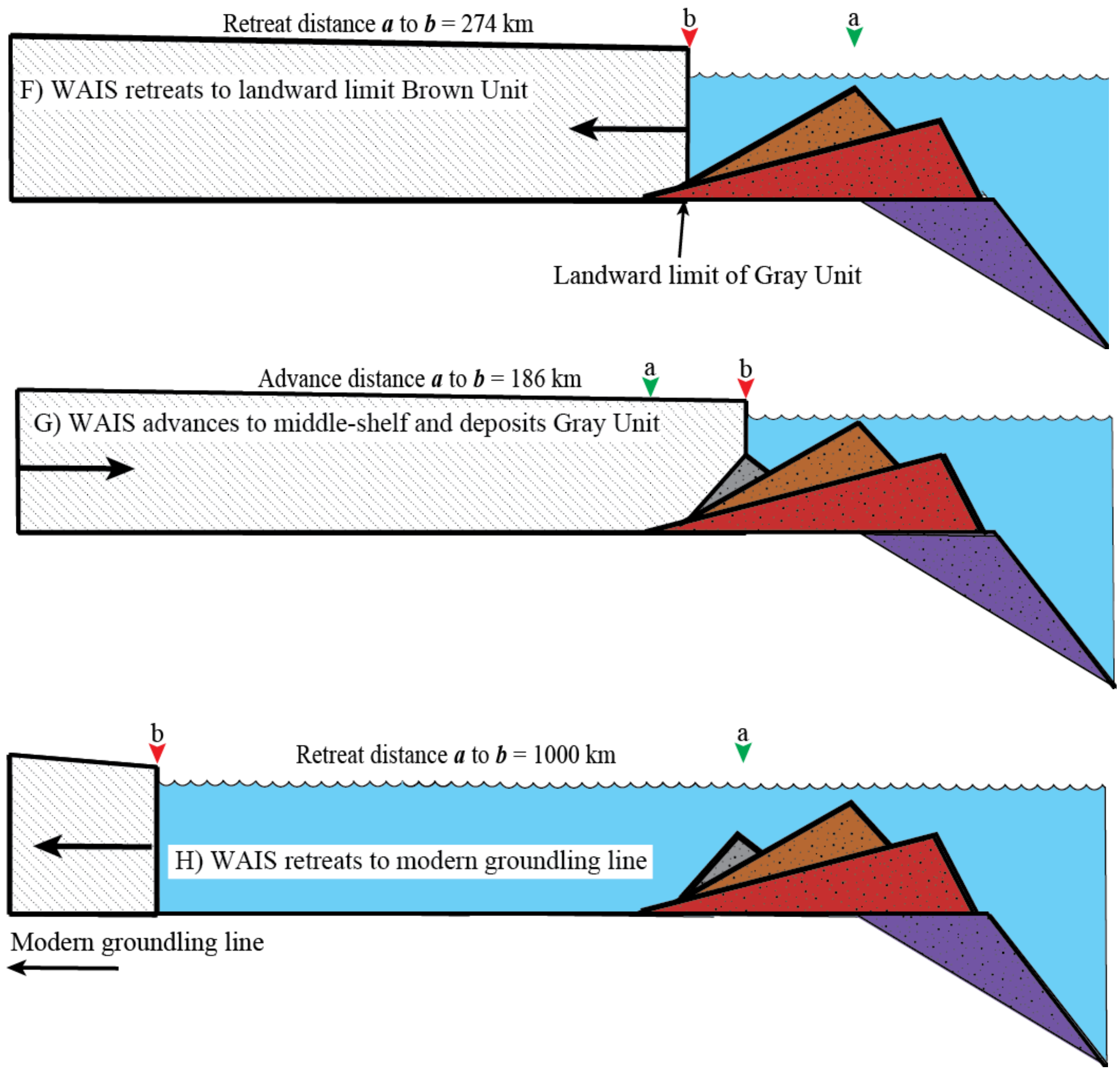
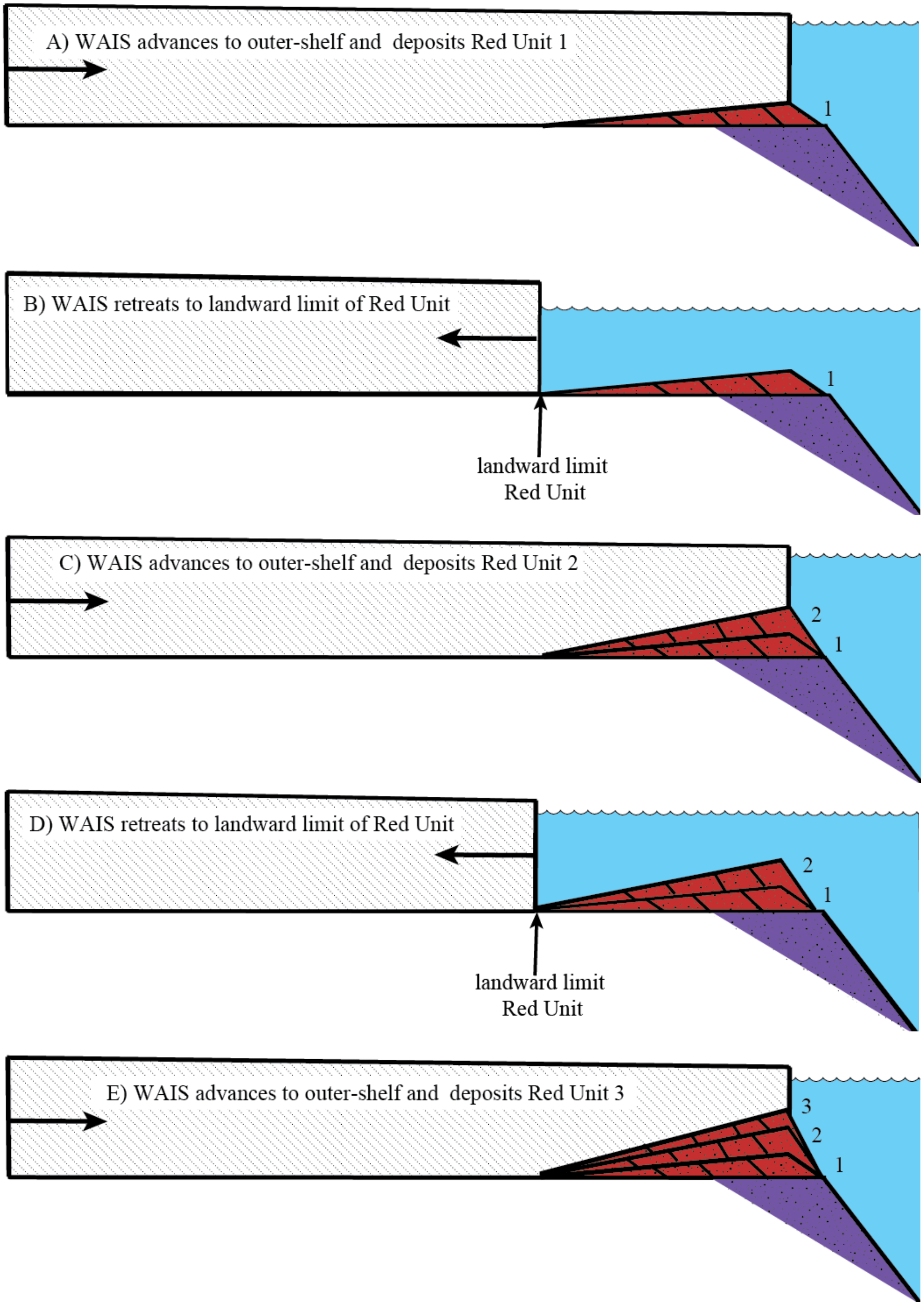


Following the strategy outlined by Bowles (2013), the Brown Unit could have been deposited as either a vertical (Figure 8) or horizontal stack of relative thin till sheets (Figure 9), each deposited in a progradational style. The vertical-stack shows the production of prograding stratal patterns in sheets of till during several successive grounding events during which the WAIS waxed and waned on the eastern Ross Sea shelf. Each advance added a vertically-appreciable thickness of till to the outer shelf. This model predicts that there should be multiple topset reflections and that there should be multiple stratigraphic levels at which prograding foresets downlap the intermediate topset surfaces (Figure 8). These stratal patterns are not observed for the Brown Unit. The top of the Brown Unit is a topset surface so if this mode of deposition occurred, then the intermediate topset surfaces should be evident. The topset reflection is a consequence of pelagic marine sediment capping diamict sediment. This stratigraphic relationship is consistent with the sedimentology found in piston cores which show the modern pelagic sediment in contact with diamict deposited during the last major grounding event (Domack et al., 1999). Based on the absence of intermediate topset reflections within the Brown Unit, the vertical-stacking progradational model is excluded from further consideration. The horizontal stacking progradational model predicts that topset reflections form many previous grounding events are decapitated during the last grounding event that defines the top of the seismically-resolved unit. The model predicts that any foreset reflection would extend from the base to the top of the seismic unit. The absence of topsets in the Brown Unit is consistent with the horizontal-stacking progradational model. The lack of foreset reflections within the Brown Unit is not viewed as particularly problematic because the Gray Unit GZW does not contain internal foreset reflections but the overall morphology confirms that the Gray Unit formed in a till delta fashion.

Moreover, the Red Unit contains few foreset reflections. Apparently, foreset reflections most represent till on till deposition. In other words, the lack of contrasts of sediment types delivered to the foreset surface means that these surfaces do not typically produce seismic reflections (Figure 9). Nonetheless, the absence of foreset reflections does not provide strong evidence that requires the progradational model of deposition.

Figure 8. WAIS Progradational Vertical Stacking Model.

(Figure 8 continued)



An outer shelf aggradational mode of deposition for the Brown Unit is provisionally excluded

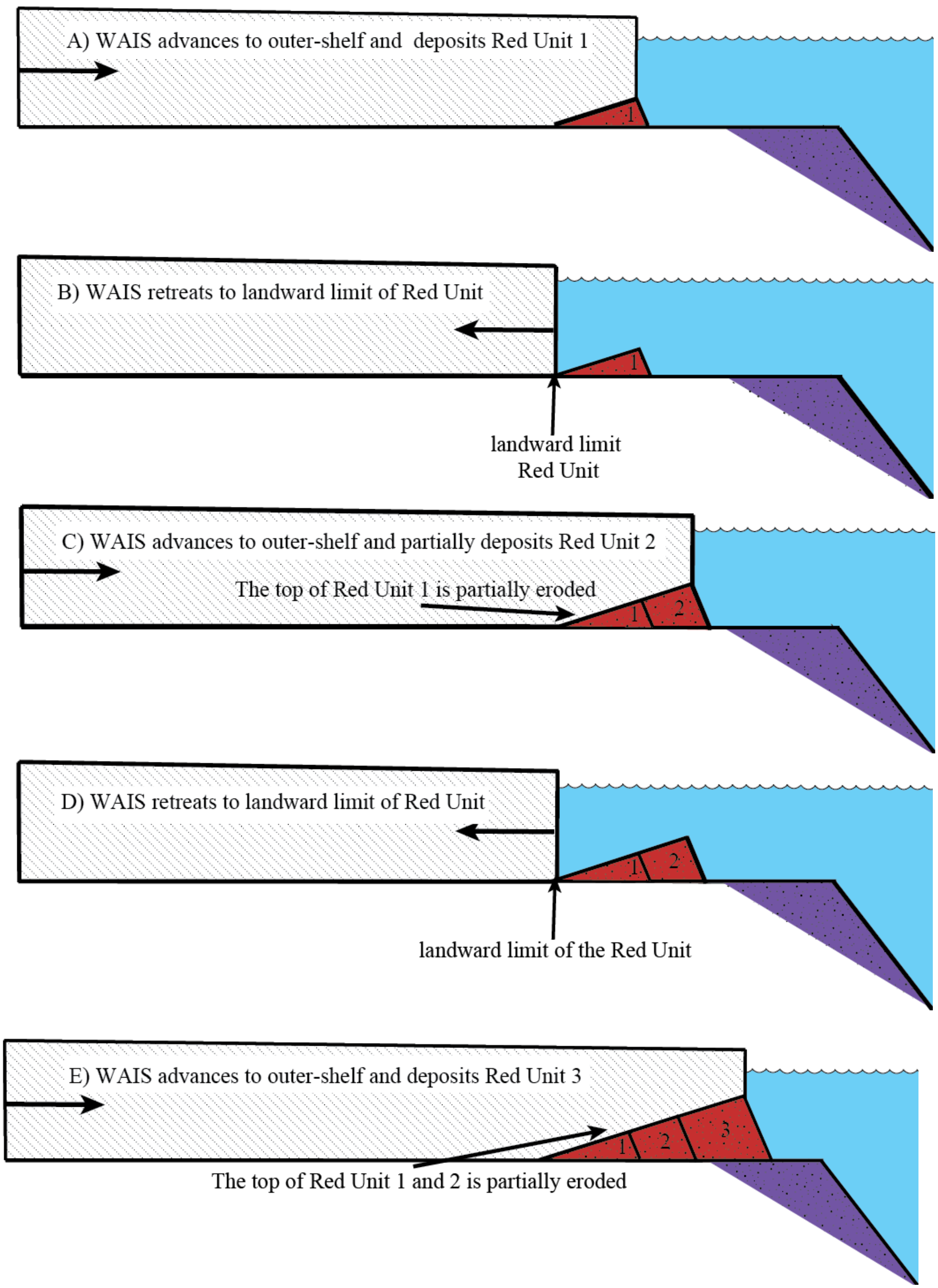
Due to the long-duration grounding line translations (previous section) and because of the evidence requiring that the Brown Unit was deposited as a progradational unit, this section considers the possibility that the Brown Unit formed as a subglacial deposit.

If deposition of the three GZWs occurred within a post LGM timeframe, it is requisite to have been by a depositional process that does not call for major grounding line translations. In other words, GZW deposition would have had to occur by subglacial aggradation. Seismic correlation by Bart and Iwai (2011) to subglacial deposits on the Antarctic Peninsula outer shelf demonstrates that appreciably thick subglacial aggradation does occur on the Antarctic shelves. Quantifying the rates of subglacial aggradation is problematic because it is difficult to access the modern subglacial settings below kilometer thick fast flowing ice (Benn and Evans, 1996).

To evaluate whether subglacial aggradation could have been the primary means by which the Brown Unit was deposited, various mechanisms of subglacial transport and sedimentation described by Evans et al. (2006) were considered. A depositional model for outer shelf subglacial aggradation is shown in Figure 10. Subglacial sliding and subsequent melt-out or lodgement must occur. Erosion of the underlying bed generally occurs as basal ice moves basinward. However, within a post-LGM warming period, ample volumes of subglacial meltwater at high pressures would have been present underneath the ice sheet. These waters would be at high pressures due to the normal force produced by the overlying mass of voluminous ice (Sylvain et al., 2012).

Figure 9. WAIS Progradational Horizontal Stacking Model.

(Figure 9 continued)



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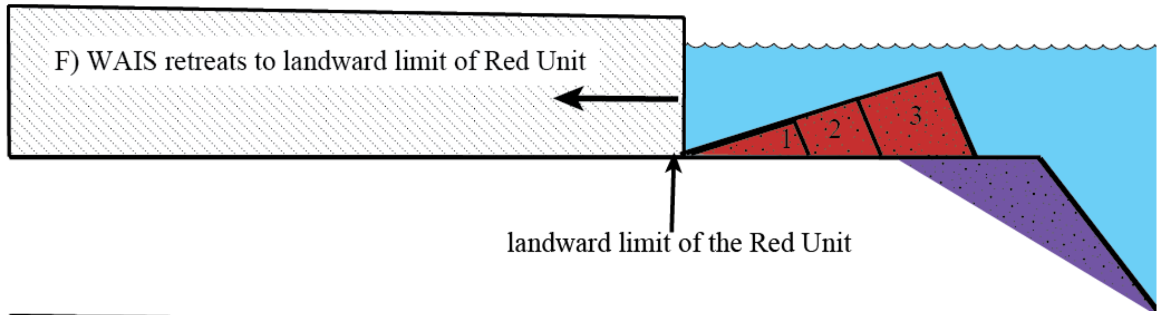
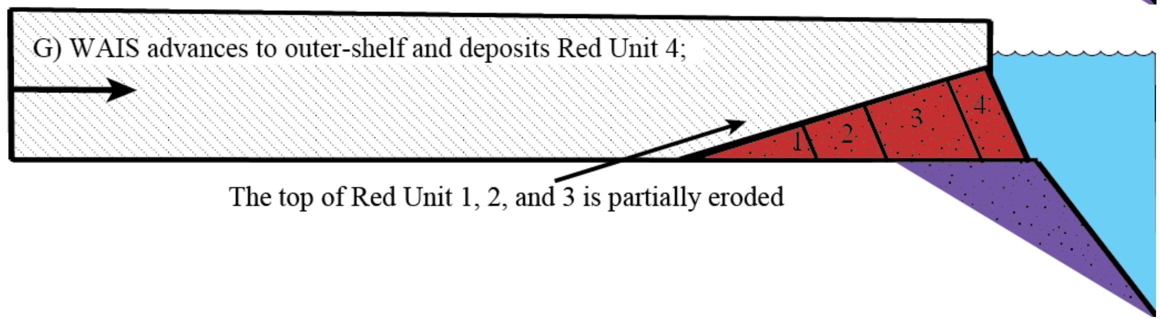
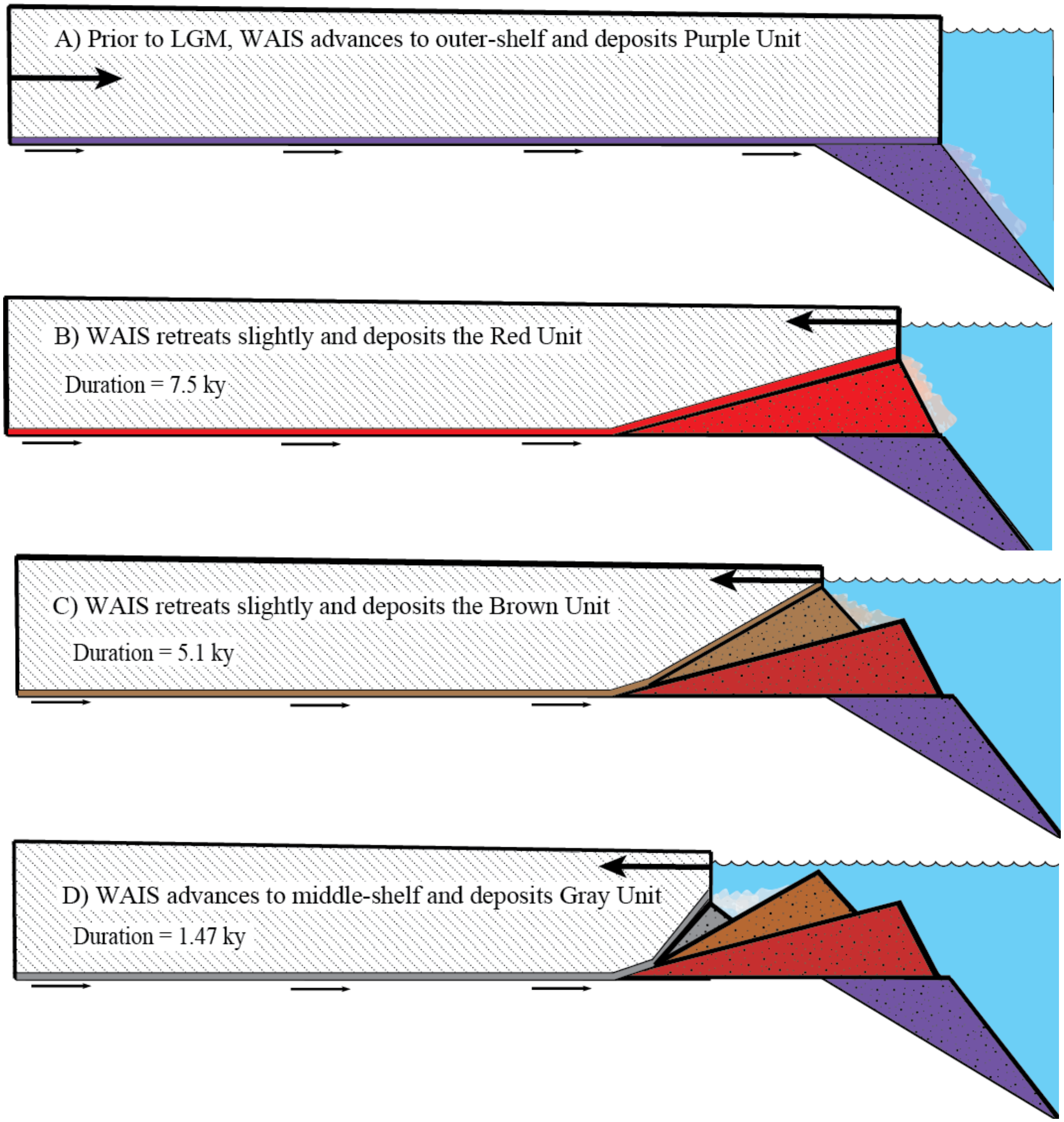




This fluidized zone along with a decoupling of the ice from the bed would have effectively reduced the transmission of stress onto the underlying seafloor. This process aids in successfully minimizing the erosional component thus allowing subglacial sliding of entrained sediment over soft beds to occur. Subglacial sliding would eventually transport sediment to the outer shelf limit of the ice sheet where these ediments would aggrade (Sylvain et al., 2012). At the outer shelf, subglacial melt-out over time could lead to the deposition of a subglacially aggraded sedimentary wedge. Evans et al. (2006) describes this process as a passive sediment release from debris-rich stagnant basal ice. For this to be a viable model for the Antarctic shelves, there must be alternating episodes of subglacial sliding of water saturated debris rich basal ice that experiences intermittent subglacial melt-out. Drainage of meltwater can occur either via meltwater channels or through the underlying sediment (Evans et al., 1996; Alley et al., 1998; Lawson et al., 1998; Roberts et al., 2002; Evans et al., 2006; Sylvain et al., 2012).

Figure 10. WAIS Aggradational Model.

(Figure 10 continued)



Lodgement is another process by which subglacial aggradation of till may occur. Evans et al. (2006) described this process as the plastering of glacial debris from a basal sliding layer to a rigid or semi-rigid bed. This mechanism could be viable on soft underlying beds if larger, clast sized particles lodge first, followed by smaller particles. When large clasts lodge into soft sediment, a prow is formed from ploughing of the deformable substrate. The prow stops the forward motion of the clast, giving rise to clast deposition (Evans et al., 1996; Alley et al., 1998; Lawson et al., 1998; Roberts et al., 2002; Evans et al., 2006). After deposition of ample amounts of large clasts, strain rates fall and allow for the accumulation of finer particles (Evans et al., 2006).

Due to a lack of direct sedimentological data available for this study and for the purposes of this study, it is impossible to differentiate if the Brown Unit is dominated by subglacial melt-out or lodgement. With that in mind, an elementary model explaining whether or not the Brown Unit could have formed by subglacial aggradation within the post-LGM window of 7.8 ky was fashioned (Figure 8).

Figure 8 demonstrates the sequence of events required to aggrade the back-stepping sequence of the Red, Brown and Gray units. This approach assumes that retreat-mode 3D flux, Q_{3DR} (Table 2) applies. Aggradational durations for each unit represents the retreat-mode grounding event duration shown in Table 2.

After the WAIS advances to the outer shelf to deposit the Purple GZW at the LGM (Figure 8A), it retreats slightly and pauses. During the pause in grounding line retreat, the Red Unit is deposited as a subglacial aggrading till sheet (Figure 8B). Based on the retreat-mode flux (Q_{3DR}= 3.24 x 10^8 m^3/a), the aggrading event lasts 7.5 ky (Table 2; Bowles, in prep.). Subsequently, the WAIS retreats slightly and pauses to deposit the Brown Unit (Figure 8C). The retreat-mode duration for this pause is 5.1 ky (Table 2). Finally, the WAIS retreats to the middle-shelf and deposits the Gray GZW in a 1.47 ky aggradational event (Bart and Owolana, 2012). Because the grounding line retreat to deposit all three GZWs is so slight (~45 km), the elapsed time is negligible (i.e., less than 400 years using retreat rate of 8.6 km/yr based on data from Conway et al., 1999, Domack et al., 1999).

Data from Boulton (1996b) suggests that it is not feasible that the Brown Unit could have been deposited by subglacial melt-out. According to Boulton (1996b), subglacial melt-out requires approximately 100 m of debris-rich ice melt to yield a subglacial till sequence 10 m thick. Based on this rate, a 1,440 m thick debris-rich ice sheet would need to melt in order to deposit the Brown Unit, which has a maximum thickness of 144 m. Similarly, a 3,870 m thick debris-rich ice sheet would be needed to melt to deposit all three GZWs (total maximum thickness of 387 m; based on data from Bart and Owolana (2012), Bowles (2013) and this study).

The necessity of having a debris rich ice thickness of this magnitude to deposit the Brown GZW is unlikely when compared to any present day thicknesses of basal ice sequences (Evans et al., 2006) at the present-day rates of ice sheet flow averaging 500 m/year.

It is difficult to assign the Brown Unit to subglacial aggradation of lodgement till. The thickness of tills produced by subglacial lodgement is difficult to quantify, however studies of modern subglacial lodgement indicate that the mechanism is not capable of yielding great thickness of till (Ruszczynska-Szenajch, 2001; Evans et al., 2006). For the reasons outlined above, the possibility that the Brown Unit was deposited by subglacial aggradation is provisionally excluded but it is acknowledged that additional data are needed to demonstrate this to be the case.

Preliminary constraints on the timing of the Brown Unit within the context of $\delta^{18}O$ cycles.

In summary, the data generated and evaluated in this study favor the view that the Brown Unit represents the amalgamation of erosion and deposition during several glacial-interglacial cycles. If the Gray Unit represents the culmination of erosion and deposition during the entire last glacial cycle, than the Brown Unit lift-off retreat would correspond to the MIS6 to MIS5e glacial to interglacial transition. The estimated advance mode duration for the Brown Unit suggests that the Brown Unit would have been deposited beginning in MIS 15. The uncertainty for the estimated elapsed time to construct the Brown Unit is large for several reasons. For example, any pre-LGM span of time of this duration (i.e., 512.88 kyr) includes a significant amount of interglacials. During the interglacials, the flux rates would have been significantly higher. The sediment deposited during the interglacials could have been significant and this sediment would have been available to be eroded during the subsequent advance of grounded ice to the outer shelf. Based on this estimate of times for which flux to the outer shelf would have been higher, the estimate of the Brown Unit duration was lowered using equation 6 (Figure 11-A). This is taking into consideration both the advance flux within the glacial cycles and retreat flux within the interglacial cycles.

On the basis of accounting for both advance and retreat modes using equation 6, the grounding event duration for the Brown Unit was estimated to have been a 125 ky period. Using a similar rationale, the duration of the Red Unit is reduced to a 140 ky period. The duration of the Gray Unit is not affected by this consideration.

Figure 11-A, pre-LGM Gray deposition

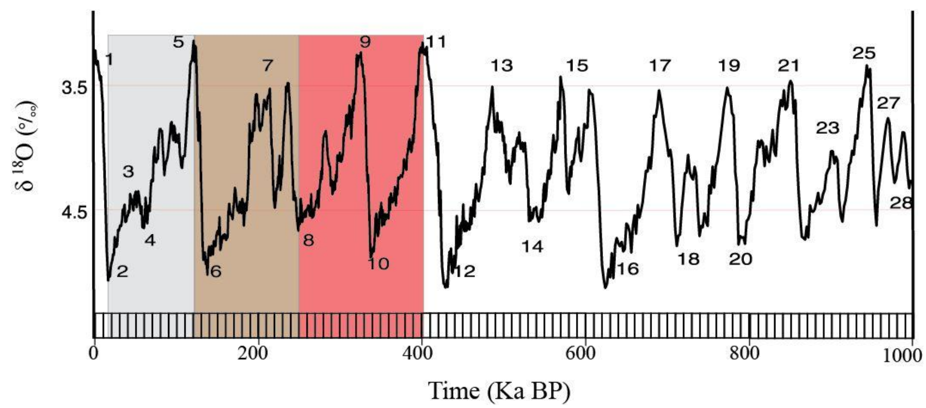


Figure 11-B, post-LGM Gray deposition

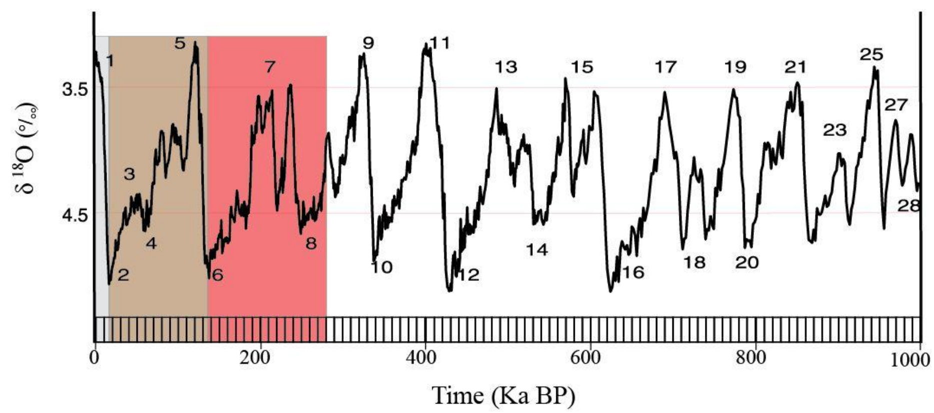


Figure 11. $\delta\ ^{18}O$ simulated ice volume curve.

The adjusted durations for the Red and Brown Units are shown on Figure 11-A. The duration of the Gray Unit is estimated to correspond to the entire last glacial cycle, i.e., MIS5e to MIS2. The longer estimated duration of the Gray Unit grounding event from Bart and Owolana (2012) is considered to be within the limits of uncertainty for the approach used to estimate the durations. However, Bart and Owolana (2012) conclude that the Gray unit could have also possibly been deposited within the smaller post-LGM timeframe. This alternative model is shown as Figure 11-B, Brown corresponds to 114 ky from MIS6 to MIS2, and Red is 145 ky, MIS 8-9 and MIS 6. Alternatively, within Figure 11-A, the Red Unit corresponds to deposition during MIS11 to MIS8, the Brown Unit is assigned to MIS8 to MIS 5e, and finally, the Gray Unit is assigned to the last glacial cycle (i.e., from MIS5e to MIS2) (Bart and Owolana, 2012). All three units (Red, Brown, and Gray) were deposited in roughly less than 400 ky over 4 glacial- interglacial cycles. These durations are shown on a $\delta^{18}O$ curve of ice volume over the past 1 million years (via stacked deep-sea core benthic $\delta^{18}O$ (Lisiecki and Raymo, 2005) (Figure 11-A).

Conclusions

1. This study aimed to deduce whether or not the Brown Unit (as defined by Bart, 2004) could have been deposited in a post-LGM timeframe. Using the framework of study adopted from Bart and Owolana (2012), the volume of the Brown Unit and its grounding event duration were estimated. The volume of the Brown Unit was estimated to be 1.45×10^{12} m^3. The advance and retreat mode durations were estimated to be 512.88 ky and 5.12 ky, respectively.

2. The advance-mode duration significantly exceeds the 7.8 ky post-LGM timeframe. The retreat-mode duration fits within the timeframe but represents 66% of the time after the LGM. When combined with retreat-mode durations for the Red (7.5 ky) and Gray Units (1.47 ky), the total elapsed time exceeds the 7.8 ky post-LGM timeframe (Bart and Owolana, 2012, Bowles, in prep.).

3. If the GZW wedges were indeed deposited by a till delta mode, then the required grounding line translations would involve significantly longer time than the post-LGM time. This experiment precludes the possibility that the three GZWs were deposited within a post-LGM timeframe.

4. Because the Brown Unit lacks prograding foresets requiring that the unit formed by till delta progradation, the possibility that the unit might represent aggradation of subglacial till was considered. The possibility that the Brown Unit is a subglacial deposit was provisionally excluded because such would require that the speed of ice stream ice flow and thickness of subglacial debris layers would far exceed reasonable limits.

5. Two modes of depositional models were considered, one being a progradational regime and the other being aggradational. The analysis suggests that the Brown Unit must represent an amalgamation of deposition and erosion over several glacial-interglacial cycles in a horizontal-stacking fashion.

6. Using the stacked deep-sea core benthic $\delta^{18}O$ curve delineating global ice volume changes of the last 1.0 Myr (Lisiecki and Raymo, 2005), the Brown Unit is assigned to MIS8 to MIS 6. All three units (Red, Brown, and Gray) were deposited in roughly less than 400 ky over 4 glacial- interglacial cycles.

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Vita

Logan Gregory Kirst was born in 1987 in Denver, Colorado. Logan, his parents and two brothers Kyle and Marshall moved to Bakersfield, California where they lived for six years, then moved to Southlake, Texas and stayed for four years, and finally settled in Kingwood, Texas where they have lived since March of 2000. Logan graduated from Kingwood High School in May of 2006. He continued on to Louisiana State University and graduated with a Bachelor of Science in Geology in December of 2010. Following graduation, Logan worked as a Mudlogging geologist in the Eagle Ford shale for eight months. He went back Louisiana State University to attain his Master of Science in Geology and anticipates graduating in May of 2013. Upon graduating from LSU with his Master of Science, Logan plans to move to Houston, Texas and work as a geologist for BHP Billiton Petroleum.